Characterization of the RHEPP 1μs Magnetic Pulse Compression Module *

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Abstract

The technology for pulsed power based high average power accelerators is being developed in the RHEPP (Repetitive High Energy Pulsed Power) project. This technology base uses magnetic pulse compression to generate repetitive, high peak power pulses. The 1 μs pulse compressor accepts 3400 V rms, 120 Hz input power from a 600-kW alternator and delivers unipolar ~1 μs rise time, 260 kV pulses to the RHEPP pulse forming line at a rate of 120 pps. The compressor consists of 5 stages of pulse compression with a 15 to 260 kV step up transformer between stages 2 and 3. Magnetic switches are used throughout the compressor because such switches seem to offer the potential of meeting the lifetime requirements of high average power systems. Thermal and electrical data has been acquired to characterize the compressor during several long duration runs (some over 1 million shots). A description of the compressor and its components along with data and a discussion of the compressors performance are presented.

Introduction

Studies showing the beneficial effects of treating various materials with x-rays or particle beams along with changing government regulations and increasing public awareness of environmental pollution issues have prompted a growing interest in high average power (HAP) accelerators. Presently, electron and ion beam accelerators operating at average power levels up to a few 100's of kW are used in several commercial applications. These applications include electron beam welding, semiconductor/surface modification, plastic polymerization, and x-ray lithography. Furthermore a new, larger class of applications requiring higher average power levels (from several 100s of kW to a few MW) seems to be on the horizon. These include flue gas cleanup, medical waste treatment, waste water treatment, drinking water treatment, and others[1]. These potential applications will require technology development, but, could represent an opportunity for pulsed power based accelerators to gain marketplace acceptance. In each case, however, other technologies (such as DC accelerators, RF accelerators, Cobalt-60 radiation sources, etc.) will be competing and acceptance will only be gained if pulsed power based accelerators are demonstrated to have acceptable performance, to be cost effective, and offer significant advantages over more conventional approaches. the technology for such demonstrations is being developed , in the Repetitive High Energy Pulsed Power (RHEPP) project[2,3].

The purpose of the RHEPP project is to develop pulsed power accelerator technology for HAP applications and demonstrate it in a prototype accelerator operating at an output power level of 350 kW. In a high average power application, an accelerator will be required to operate efficiently and reliably for a long time (5 years or more). Consequently, at the onset of the project, the following criteria were adopted for use in selecting and designing all of the components in the system;

1) Low losses, component efficiency > 0.9-0.99
2) High Reliability, > 10^8 shots without maintenance
3) Long Lifetime, 10^9-10^{10} shots

These criteria are representative of the performance that will be required in a typical commercial application. In order to develop such components, several technical issues must be resolved. The key technical issues that were identified at the onset of the RHEPP project were;

1) Thermal management of energy losses throughout the machine,
2) The development of long life, high current diodes, and,
3) Establishment of electrical stress levels in insulations which yield acceptable lifetimes in repetitive pulse applications.

The first issue has been addressed by developing a strong thermal modeling capability within the RHEPP project and applying this capability as an integral part of each component design. The development of this capability, which included small scale experiments and modeling with a commercial heat transfer and flow analysis code, is described in reference [4]. The second issue is being addressed by an experimental effort within the RHEPP project which is going on in parallel with the accelerator development. These experiments are being conducted in a dedicated 250 kV, 500 Hz, 35 kW test bed and recent results are described in reference [5]. The third issue is complex because of the extent of the parameter space involved and would take many years (or accelerated test proceedures) to thoroughly address. The approach that has been taken in the RHEPP project thus far is to use relatively conservative electric field stress limits (based on the sparse information currently available) for the initial component designs. Then, after the accelerator is operational, several insulation experiments will be conducted in parallel with accelerator operations. This will lead to improved and more compact component designs in the future.

A block diagram of the RHEPP system is shown in Fig. 1A. The RHEPP accelerator is designed to accept 670 kW of power from the local power grid and deliver 2.5 MV, 60 ns FWHM, 2.9 kJ pulses to an 88 Ω electron beam diode load at a rate of 120 pulses/sec (pps). As a prototype, the RHEPP topology is not intended to be optimal for any specific application, but, should serve well in the accomplishment of its primary mission: to develop and demonstrate key component technologies. It is generally accepted that magnetic switches will be a key component in the pulse compression scheme of any short pulse HAP accelerator. Similarly, a linear induction voltage adder (LIVA) with magnetic blocking cores will almost certainly be required in any high voltage (>1 MV) short pulse HAP accelerator. Consequently, pulse compression in the RHEPP 1μs and 60 ns compressors (spanning the ms to ns time scales) is accomplished exclusively with magnetic switches and voltage multiplication to the 2.5 MV level will be accomplished in a LIVA with Metglas blocking cores. The system is presently coupled to the local power grid by a motor driven, 600 kW, 120 Hz alternator. For most applications, this will probably not be the best way to couple to the power source so investigations into other options (including solid state switches) are planned. Construction and preliminary testing of the accelerator subsystems has thus far progressed along 3 parallel paths as depicted in Fig 1B. The 1μs Compressor, which is described below, has been tested at full power, with the alternator driver, into a resistive load. The 60 ns Compressor/pulse forming line (PFL) has been tested at lower power levels (up to 20 kW, 5 Hz) with a Marx bank driver. The PFL has an output impedance of 0.88 Ω and is connected to its load by 50, 44 Ω

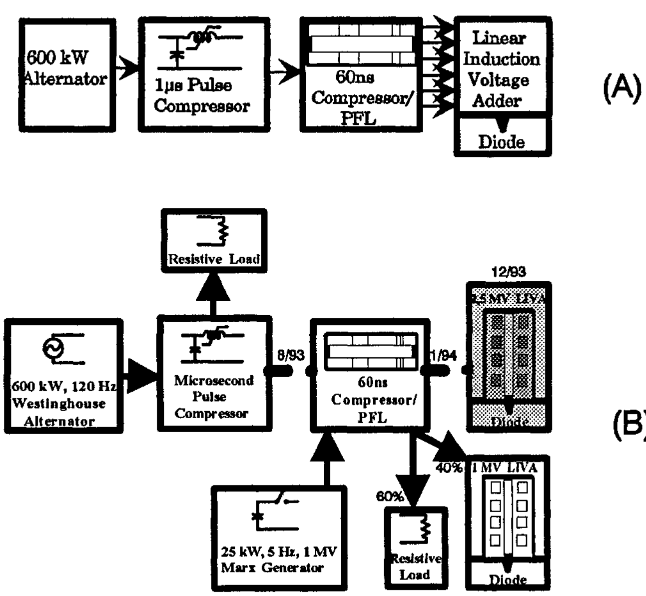

Fig. 1. Block diagrams of the RHEPP system; (A) Basic system, and (B) Current status of the system.

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14. ABSTRACT
The technology for pulsed power based high average power accelerators is being developed in the RHEPP (Repetitive High Energy Pulsed Power) project. This technology base uses magnetic pulse compression to generate repetitive, high peak power pulses. The I J.lS pulse compressor accepts 3400 V rms, 120 Hz input power from a 600-kW alternator and delivers unipolar -I J.lS rise time, 260 kV pulses to the RHEPP pulse forming line at a rate of 120 pps. The compressor consists of 5 stages of pulse compression with a 15 to 260 kV step up transformer between stages 2 and 3. Magnetic switches are used throughout the compressor because such switches seem to offer the potential of meeting the lifetime requirements of high average power systems. Thermal and electrical data has been acquired to characterize the compressor during several long duration runs (some over I million shots). A description of the compressor and its components along with data and a discussion of the compressors performance are presented.

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cables (Dielectric Sciences #2158). For these initial tests, 20 of the cables have been directed to a 4 stage, 35 Ω,1 MV LIVA with both electron and ion beam loads. The balance of the cables are connected to resistive dummy loads. These tests have been useful in checking out the PFL system, acquiring information from the operation of the 1 MV LIVA for use in the design of the 2.5 MV LIVA, and performing diode experiments at the 1 MV, few kW level. Results from these tests are described in reference[6]. The 2.5 MV LIVA has been designed and is now being fabricated. At the end of this summer, the PFL and 1 MV LIVA are scheduled to be connected to the 1µs Compressor and tested at full power. During these tests, several diodes will be fielded for testing at the 1 MV, 150 kW level. The 2.5 MV LIVA is expected to be completed by the end of this year, so full power testing of the complete RHEPP accelerator should begin early next year.

1µs Compressor Description

The 1µs compressor circuit is shown in Fig. 2. It is designed to accept 600 kW of input power at 3400 Vrms from a 120 Hz, Westinghouse alternator [7], and deliver unipolar, 260 kV, 4.5 kJ pulses, at a rate of 120 pps, to the 130 nF input capacity of the PFL with times to peak of 1 µs. For the most part, the circuit is a common magnetic pulse compressor, and detailed descriptions of its operation along with discussions of magnetic switch theory can be found in the literature [8]. The first loop in the circuit is resonant with the alternator so that the voltage on the first capacitor rings up to 15 kV as shown in the typical VC1 waveform of in Fig.1. The first magnetic switch (MS1) saturates when VC1 reaches the positive peak and a 15 kV pulse is launched down the pulse compression chain toward the load. An 18 to 1 step up transformer between the second and third compression stages elevates the voltage to ~ 260 kV.

All of the compressor's magnetic switch designs involved extensive electrical, mechanical, and thermal analyses. The primary criteria used in each design were;

1) Pulse compression factor near 5,
2) Maximum local electric field stress < 50 kV/cm,
3) Losses in the device < 6 kW (1% of input), and
4) Maximum local temperature < 100°C.

A photograph of the compressor, in its 12' x 24' x 5' oil tank, is shown in Fig. 3. During operation, the tank is filled with transformer oil which serves as an electrical insulating medium and as a coolant. The oil is circulated, by small pumps located in the tank, through cooling channels in each of the switches and the transformer. The bulk oil in the tank is also circulated at a rate of ~60 gal/min through a 60 kW heat exchanger. Each of the switches and the transformer are vacuum impregnated with oil to minimize the probability of air bubbles being trapped in high electrical stress regions. Fiberglass buckets (4' in diameter) keep these devices under oil when it is necessary to drain the main tank. A summary of data on the 5 magnetic switches and the transformer is given in Table I. The designs for the low voltage switches (MS1 and MS2) are very similar and, likewise, the designs for high voltage switches (MS3, MS4, and MS5) are very similar. A photograph of MS1 is shown in Fig. 4 and a photograph of MS4 is shown in Fig. 5. Lower cost, conventional silicon steel, cut cores are used in the low voltage switches because the magnetization rates are relatively low. These switches are constructed by stacking several 4" wide cores vertically and wrapping the coils on the cores as shown in Fig. 4. Initially, all the switch coils were wound with Litz wire[9] to ensure uniform current distributions

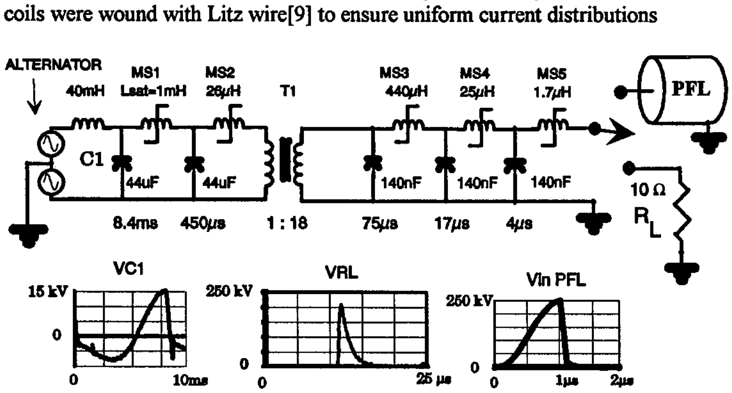

Fig. 2. 1µs compressor circuit with some typical waveforms.

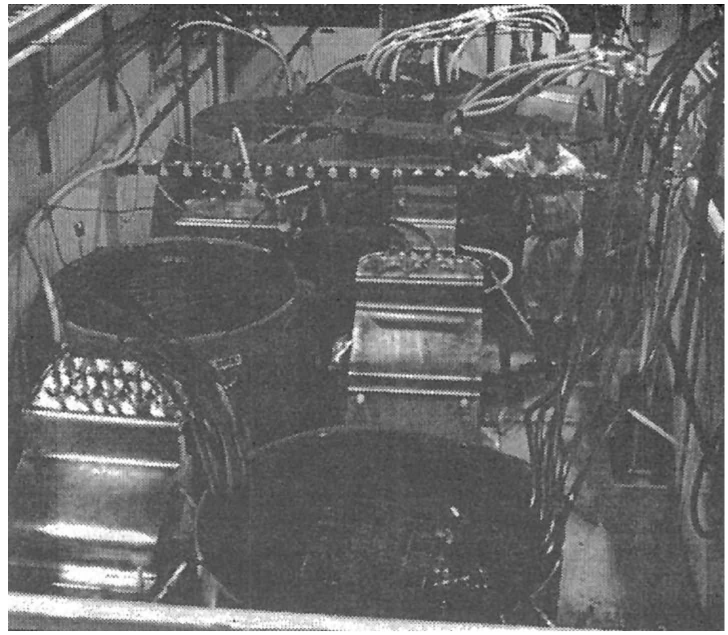

Fig. 3. Overhead photograph of the 1µs compressor.

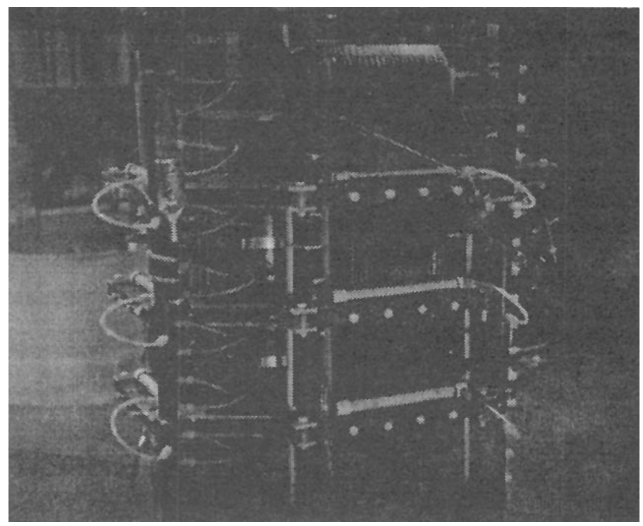

Fig. 4. Photograph of MS1.

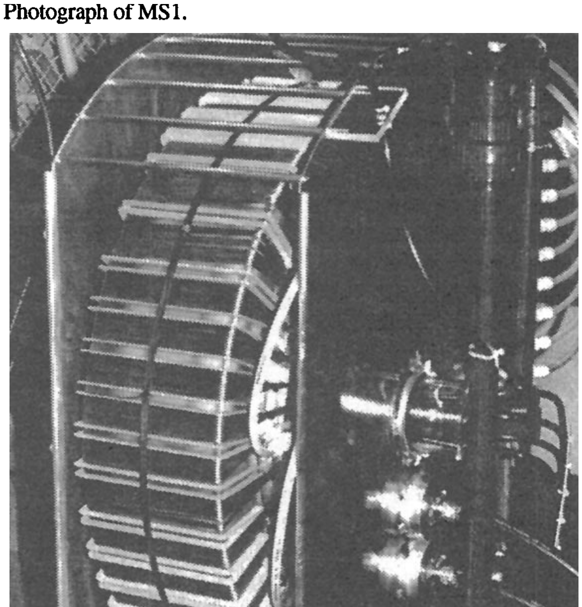

Fig. 5. Photograph of MS4.

in the coil crossections. The cores for the high voltage switches were toroids of field annealed 2605CO Metglas (6" wide,15" ID, and 25" OD). Insulation in the MS3 core is provided by a plastic coating (~.125 mil thick) which was electrophoretically applied to the Metglas at Sandia [10]. Coated Metglas was not used in the MS4 and MS5 cores because it was not practical to coat the required quantity of Metglas in the time demanded by the project schedule. Polycarbonate films were used for insulation in MS4 (.25 mil thick) and MS5 (.5 mil thick). The toroids were wound on Lucite mandrels and the outer circumferences of the toroids were covered by Lucite shells. The switches were constructed by standing the toroids up (axis horizontal) and wrapping the coils over the mandrels and the shells as shown in Fig. 5. Connections between the high voltage switches and their capacitor banks or the load are done with standard RG-220 coaxial cables. A photograph of the transformer is shown in Fig. 6. It was designed by Westinghouse[11] and constructed by Sandia. It has a conventional silicon steel cut core with a 9 turn copper sheet (23" wide, 10 mils thick) primary winding and 162 turn magnet wire (#14 AWG) secondary winding.

Single Shot Testing

Prior to installation and vacuum impregnation, the saturated inductance and volt-second product of each switch was measured in the simple test circuit of Fig. 7A . The values given in Table I were acquired by this method. The stray inductance in the last loop of the compressor was expected to be significant compared to the 1.7 μH saturated inductance of MS5, thus, the total inductance of this loop was measured in the circuit of Fig. 7B. The measured inductance was 2.2 μH which will yield a charge time of ~1.2 μs for the PFL. An estimate of the compressor's energy efficiency was also obtained in a single shot mode with the circuit of Fig. 7C. Resistive voltage dividers and Pearson current transformers were used to make voltage and current measurements. Some typical waveforms are shown in Fig. 7C. These waveforms agree well (within +/- 5%) with corresponding waveforms

Device	VS	Tsat (μs)	Tdis (μs)	Vpeak (kV)	Lsat (μH)	Core Mat.	Core Amag (m^2)	Core Mass (kg)	Core insulation	Coil Mat.	Coil Turns	Shots (millions)
MS1	23	8333	450	15	900	9 mil Si Steel	0.07	760	manufacure coating	A-Litz B-#2	83	A - 1 B - 3.5
MS2	2.8	450	75	15	26	2 mil Si Steel	0.07	760	manufacture coating	Litz	12	4.5
T1	-	-	75	260	-	2 mil Si Steel	0.038	720	manufacture coating	-	P - 9 S-162	2.25
MS3	6.9	75	17	260	440	2605 CO FA Met.	0.024	363	EP coating	A-Litz B-#8	87	A- 1 B -1.25
MS4	1.73	17	4	260	25	2605 CO FA Met.	0.023	351	0.25 mil polycarb.	Litz	21	1.25
MS5	0.36	4	1.2	260	1.7	2605 CO FA Met.	0.021	314	0.5 mil polycarb.	Litz	5	1.25

Table I. Sumary of data on the magnetic switches and the transformer.

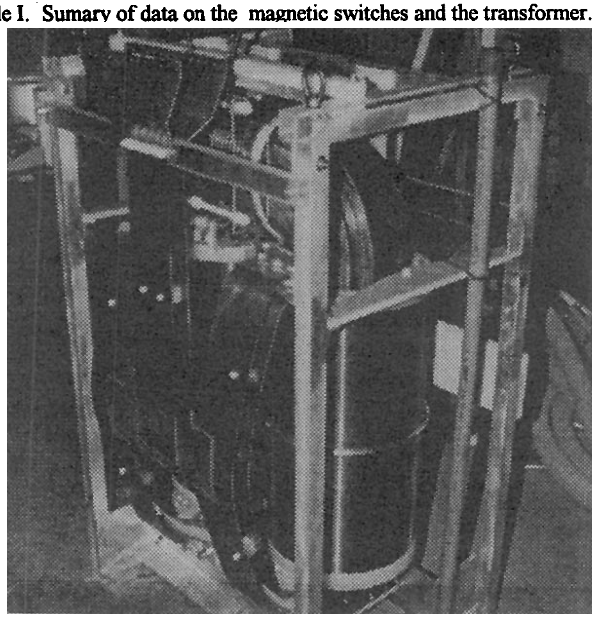

Fig. 6. Photograph of the 260 kV transformer.

from PSPICE circuit simulations. However, when these measurements are used to derive energy efficiency numbers, the error bars are large because with our present test equipment, it is difficult make pulsed voltage and current measurements with better than +/- 5% accuracy. A better estimate of the efficiency was obtained in the following manner. The charge voltage on the first capacitor was measured with a calibrated 1% electrostatic voltmeter and the temperature change of water in the load resistor was measured with a Luxtron fiber optic temperature sensor. The input and output energies were derived from these measurements, yielding an efficiency of 89+/-3%. These results are encouraging because they indicate that the compressor is very close to meeting its electrical design goals. However, more accurate measurements during repetitive operation will be required before definite conclusions can be drawn concerning the compressor's electrical performance.

Repetitive Testing

The compressor has been operated at full power in several long duration runs. The most significant of these runs are summarized in Table II. There have been 3 phases in the development of the compressor; first, the low voltage section (through MS2), then the initial high voltage section (through MS3), and finally, the full compressor (through MS5). A 2 hour and 20

Date	# of Runs	# of Stages	Duration	Significance
5-92	many	2	< 20 min.	system shakedown
6-92	1	2	94 min.	thermally induced MS1 coil failure
7-92	1	2	140 min.	low voltage section stability demonstrated
10-92	1	3	140 min.	1st high voltage stage demonstrated
5-93	1	5	30 min.	Litz coil failure in MS3
6-93	1	5	140 min.	full compressor stability demonstrated

Table II. Summary of repetitive runs.

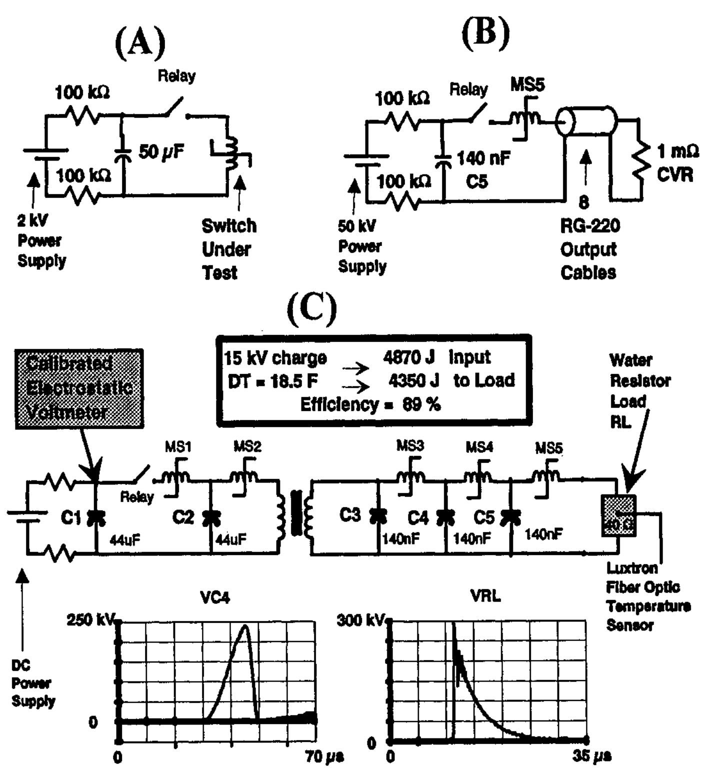

Fig. 7. Single shot test circuits for measuring; (A) VS and Lsat of switches, (B) compressor's output inductance, and (c) compressor's efficiency.

minute, 1 million shot, full power run into a resistive load was performed at the end of each of the phases. The purpose of these runs was to demonstrate, for the components involved, the following;

1) Integrity of the electrical design (proper pulse compression),
2) Successful thermal management (acceptable steady state temperatures),
3) Stable operation (for the duration of the test), and
4) A lifetime of at least 1 million shots.

The diagnostics included; resistive voltage dividers on the capacitors and the load, Pearson current transformers, and Luxtron fiber optic temperature sensors embeded in the switch cores and coils.

As Table II shows, two switch coil faults have been observed. The first, in MS1, was thermally induced and is very well understood. In the thermal analysis of this coil, it was necessary to make several assumptions. Uniform flow in cooling channels and perfect Litz wire stacks were among these. In reality it was not possible to wind perfect Litz wire stacks or get uniform flow in the cooling channels with the original manifold design. These shortcomings were rectified when the MS1 coil was rewound. The new coil was wound with a standard #2 AWG wire to simplify the fabrication process and a better coolant manifold was used to ensure more uniform flow in the cooling channels. With these modifications, MS1 has operated for > 3.5 million shots and the steady state temperatures in the coil are well below 150°F (The original coil exceeded 210°F before it failed). The second fault occurred in the MS3 coil after the switch had operated for >1 million shots. This fault seemed to originate with the Litz wire (all visible damage was either on the Litz or in the plastic just under the Litz), but, the cause is not yet understood. We speculate that the tiny Litz wire strands (#36 AWG) may be to fragile to withstand the repetitive pulsing without fatiguing and breaking. Consequently, the coil was rewound with a solid core #8 AWG wire and has operated with no visible problems for > 1.25 million shots. This problem will require further study, but, if it is simply due to a weakness in the Litz wire, it can easily be solved by replacing the Litz wire in the other switches. This could lead to higher coil losses if highly non-uniform current distributions develop, but, in MS1 and MS3 no significant increases in losses have been observed.

Aside from these occurrences, the compressor has performed essentially as designed. All of the components have steady state temperatures within design limits and, with the exception of MS2, these temperatures are below 150°F. This demonstrates that the thermal management technology in the compressor is well developed. The operation of the compressor is also very stable. No detailed study has been conducted, but, fluctuation in voltage and current waveforms is definitely well under 10 %. Typical waveforms are shown in Fig. 8. To within measurement accuracy, the waveforms are as expected. This, along with the results of the single shot tests, demonstrates that the compressor is performing well electrically and is capable of continuous operation at the 600 kW level for at least 1 million shots.

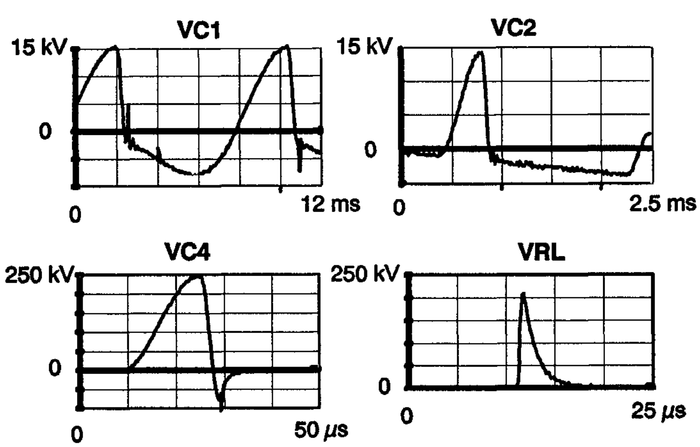

Fig. 8. Some typical waveforms from repetitive operation into a 10 Ω load.

Conclusions

The RHEPP 1μs compressor is successfully demonstrating the technology that will be required in pulsed power based high average power accelerators. The compressor has demonstrated operation at the 600 kW level in a 2 hour and 20 minute, 1 million shot, continuous run. Thermal management technology is well developed as demonstrated by the acceptable steady state temperatures in all components. The energy efficiency of the compressor appears to be 89 +/- 3 % and the output inductance is 2.2 μH. This will yield a 1.2 μs charge time for the RHEPP PFL. The compressor operation is stable and the electrical waveforms are as expected. A fault in the MS3 coil, which may be exposing a weakness in the Litz wire windings, is being studied. If the study confirms this suspicion, it will be necessary to replace the Litz wire in the coils of MS4, MS5, and possibly MS2. At the end of this summer, the compressor will be connected to the PFL and the 1 MV LIVA so that these systems can be tested at full power. It will also be possible to test several electron beam diodes at the 1 MV, 150 kW level. The 2.5 MV RHEPP LIVA will be completed by the end of the year and testing of the completed RHEPP accelerator, with 350 kW of power to the diode load, should begin early next year.

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